Analysis of the Power Quality Impact of Multiple Directed Energy Loads on an Electric Ship Power System

Robert E. Hebner and Angelo L. Gattozzi

Center for Electromechanics
The University of Texas at Austin
1 University Station #R7000
Austin, TX 78712 USA
512-232-1628

Keith R. Cohn and William B. Colson

Naval Postgraduate School
Physics Department
833 Dyer Road, Building 232, Room 203
Monterey, CA 93943-5117 USA
831.656.2765

ABSTRACT

The electrical power system of an all-electric ship has been modeled in Simulink for the case of a ship supporting several high power directed energy loads, among which are a Free Electron Laser (FEL), an Active Denial System (ADS), and a Laser Weapon System (LaWS). Starting from a load centered approach, and a physical description of the components of the various loads, individual models of each load plus a combined model for a system supporting simultaneously one instance of all loads have been developed. Sample case studies are presented corresponding to expected operational scenarios for a US Navy ship and to potential emergency conditions. The models have been designed to be interactive, allowing the operator to change key settings dynamically while the simulation is running, thus mimicking an actual operation of the power system on a ship in real time. A preliminary graphical user interface has also been developed to demonstrate the ability of these models to be converted into top-level training tools for Navy personnel supported by a realistic representation of the ship power system.

INTRODUCTION

The power system of an all-electric ship serves a variety of shipboard loads with a high degree of reliability and quality. Shipboard loads consist of continuous duty loads, like hotel and propulsion, as well as intermittent duty loads, as in the case of electromagnetic launchers and radar. The characteristics and requirements of the loads vary considerably. Even though some of these loads are still subject of ongoing research and development, it is important to understand how they can be integrated in the shipboard electrical system and how they will dynamically interact with each other. The profiles of intermittent duty cycle loads like the FEL, ADS, and LaWS are of particular concern due to their power demands, resulting in high short-time currents drawn in a discontinuous fashion. In fact the instantaneous power required by these loads can be a substantial fraction of the total installed system capacity, raising technical questions like transient response, instability, brownout, and compromised power quality.

To address these issues, a notional electrical power system of an all-electric ship has been modeled in Simulink for the case of a ship supporting several high power directed energy loads. A “load centered” approach has been pursued in the development of all the models: first of all, load requirements have been defined in detail and then, proceeding from them, a system has been designed so as to support adequately the given loads with appropriate power sources. The various loads modeled are:

a. Free Electron Laser (FEL)
b. AN/SQQ-90 Sonar System (SONAR)
c. Electromagnetic Railgun (EMRG)
d. Active Denial System (ADS)
e. Advanced Radar (RADAR)
f. Electro-Magnetic Aircraft Launch System (EMALS)
g. Laser Weapon System (LaWS)
h. Propulsion
i. Hotel

Thus, starting from a physical description of the various loads, individual models of each load plus a combined model for a system supporting simultaneously all loads have been developed. These models have been used to characterize the potential impact of the corresponding high power loads on a ship power system aiming at preparing the engineering basis for a smooth transition from the scientific R&D to an effective implementation on board. In particular, this work addresses the following practical objectives:

a. Sketch the probable system architecture
b. Determine the needed infrastructure and supporting equipment for the expected loads
c. Assess the general power requirements
d. Anticipate the possible time-dependent power profiles based on expected operational scenarios and its impact on the various components
e. Give a general outline of the control scheme
f. Study power quality issues
g. Study transient effects on system performance
h. Assess system stability
i. Establish component stress levels and required rating
j. Determine needed redundancies
k. Estimate the heat rejection and thermal management requirements
l. Provide a realistic basis for a real time simulator for personnel training

Among the loads, the most detailed information was received for the FEL which will, therefore, be used herein as the sample for the description of the modeling process, with the understanding that similar considerations apply to the other loads as well. Where necessary, some assumptions had to be made to generate working models, like probable architecture of the power system, reasonable performance parameters of components, etc., so that the present work provides at least a framework that can easily be completed as necessary without excessive re-work, once test data become available.

EXAMPLE OF A LOAD MODEL: THE FEL

The FEL is a device that, like a conventional laser, produces coherent radiation, but that can be designed to produce virtually any wavelength, including wavelengths not achievable with conventional sources [1]. Furthermore, FEL technology can scale to weapons-class power levels. These advantages make FELs attractive candidates for ship based antimissile weapons [2]. The FEL uses a pulsed beam of unbound (free) electrons to couple energy into the optical field. The electrons are accelerated to very high energies – near the speed of light – using linear accelerators (linacs). Then, the beam passes through a series of magnets of alternating polarity (the undulator), that through Lorentz force interactions impose an acceleration, and thus a radiative load, onto the beam. Coherence arises from a wavelength-scale bunching of the electron beam, which results from feedback between the beam and the generated light.

The frequency of the emitted radiation is solely a function of the electron beam and undulator properties. Additionally, many FEL wavelengths are quickly tunable over a relatively wide range by varying said properties. In a typical FEL, only about 1% of the energy of the electron beam is converted into photons as the beam traverses the undulator. To compensate the inherent inefficiency of this process, the residual beam is recirculated through the linac in a manner that decelerates the spent electrons so that much of the energy contained therein is recovered back into the accelerating field. This special arrangement is anticipated to increase the overall wall plug efficiency to about 20% [3].

The summary of all FEL related loads is given in Table 1 and their impacts on some expected operational scenarios are given in Table 2. A conceptual schematic diagram for the FEL is shown in Figure 1 and its corresponding Simulink model is shown in Figure 2.

Table 1. FEL Load Summary

System	Power (kW)	Voltage
Cryogenics System	1000	450 VAC
Cathode	500	500 kVDC
RF Power	16000	45 kVDC
Beam Dump	7700	4160 VAC
Magnets	300	600 VDC
Cooling	300	4160 VAC
Beam Control	20	450 VAC
Vacuum Pumps	5	450 VAC
Computers	5	112.5 VAC
Housekeeping	5	112.5 VAC
Optics	1	112.5 VAC
Fire Control	unknown	unknown
Vibration Suppression	unknown	unknown

Table 2. FEL Operation Summary

State	Description	Power (kW)
Pier Side	FEL in minimal power state; necessary maintenance performed	425
Underway	Ship crossing open waters; no imminent threat	1325
Operational Readiness	Ship is in combat theater; threat could appear at any time	1775
Hot Standby	Threat is detected; FEL is fully energized	25000
Engagement	FEL is firing upon incoming threat	25020

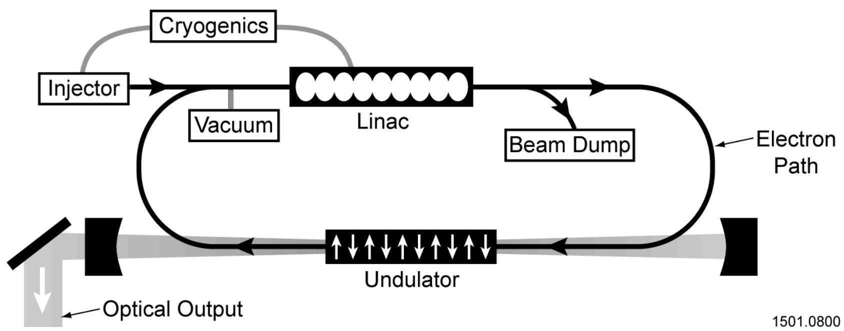

Figure 1. Schematic diagram of the FEL.

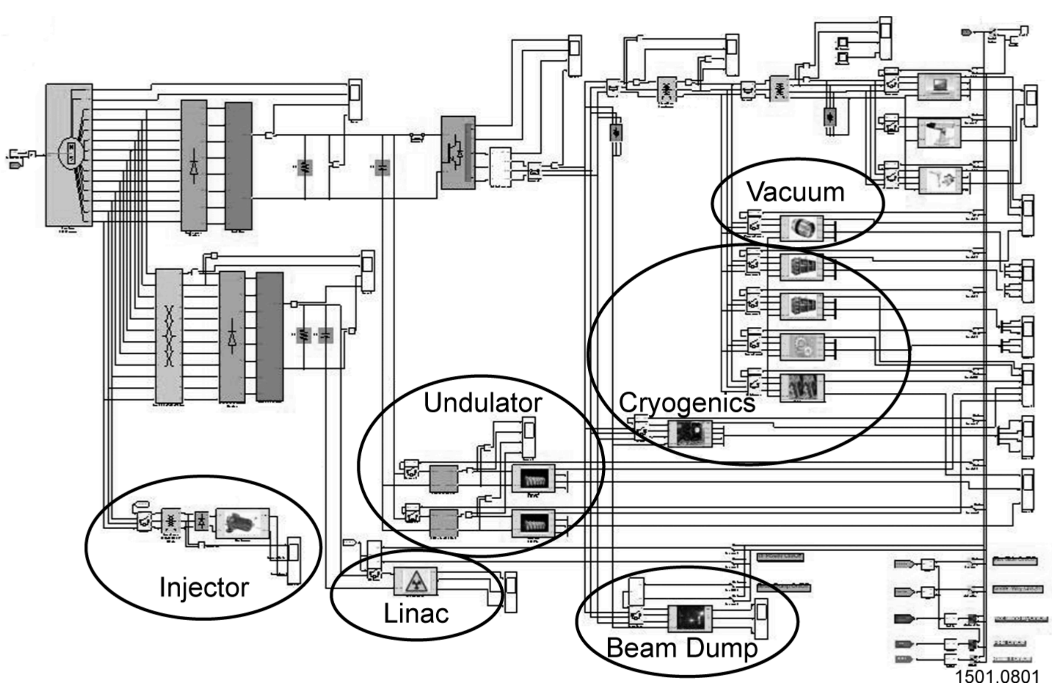

Figure 2. Simulink model of the FEL.

THE COMPLETE MODEL

Following the same pattern used for the FEL, the loads were modeled and a combined model for a notional power system supporting one instance of each load was developed. The complete model is too complex to be summarized, but it has all the loads, including the FEL, and the power system in a single coupled model. All these models have been designed to be interactive, allowing the operator to change key settings dynamically while the simulation is running, thus mimicking an operation of the system on a ship in real time. This model allows studying the response of the ship's power system to many potential operational scenarios. One obvious output of the simulation is the evolution in time of the power demand imposed by the operation of the various loads. However, the model gives the ability to probe in detail the time dependence of all physical variables of interest, as is demonstrated, e.g., in the plots reported in Figure 3 showing how starting the large cooling units in the FEL reflect throughout the system producing a perturbation back to the main generator. This is important in cases of possible fault events that may take place. For example, one simulation was carried out on the assumption that one of the phases of the main 12-phase generator supplying all loads except propulsion suddenly opened, giving the sets of plots shown in Figure 4. Another example is given in Figure 5 that shows some of the variables affected by a sudden low impedance fault line-to-line at the level of the 450 Vac bus in proximity of the SONAR and EMALS.

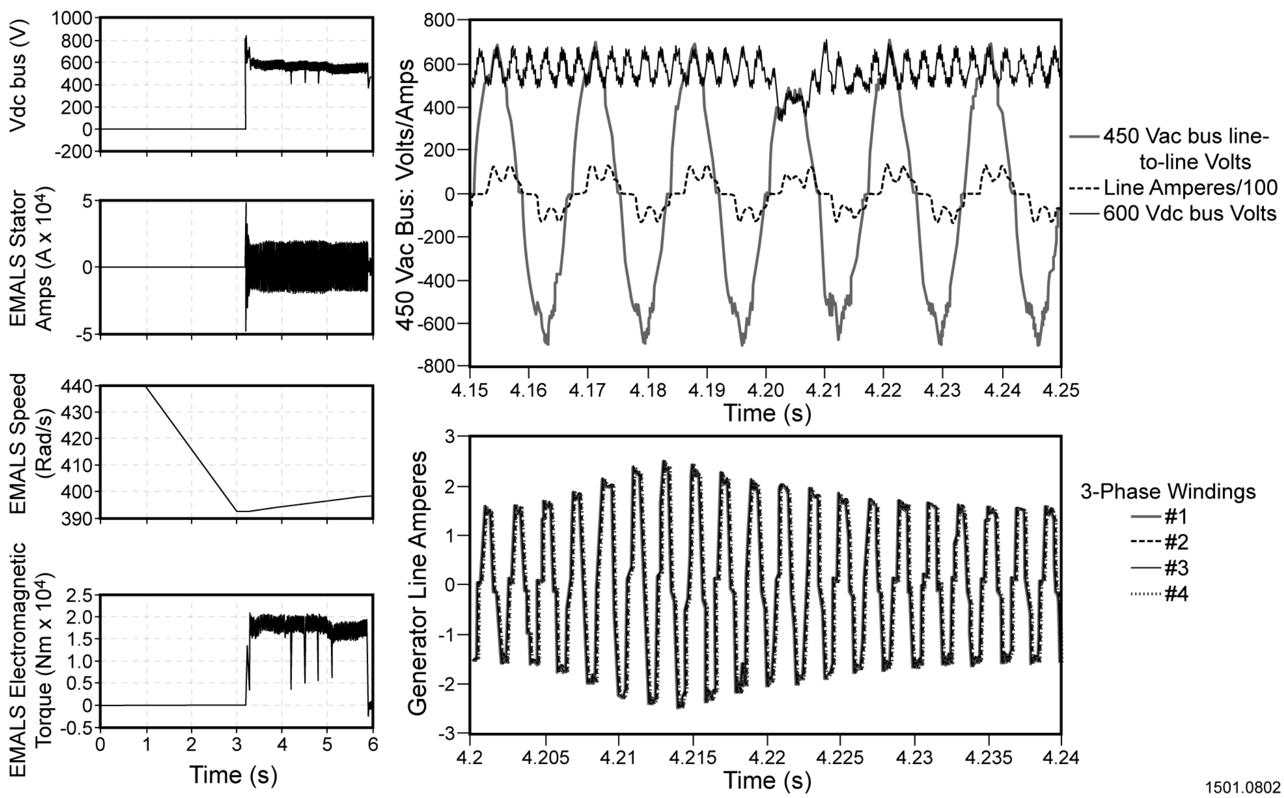

Figure 3. Perturbations induced by starting the FEL cooling units.

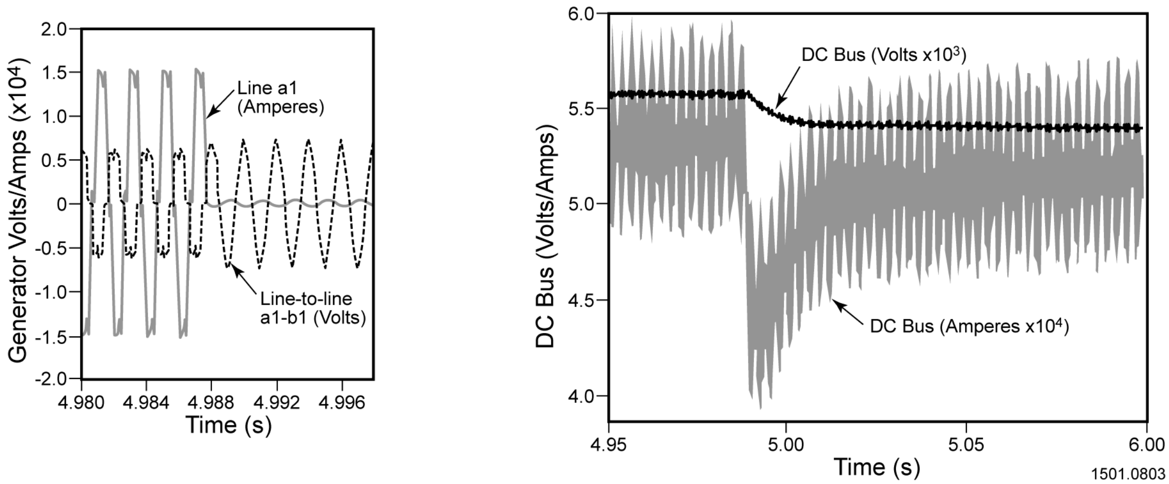

Figure 4. Some of the transients upon loss of one phase of main generator.

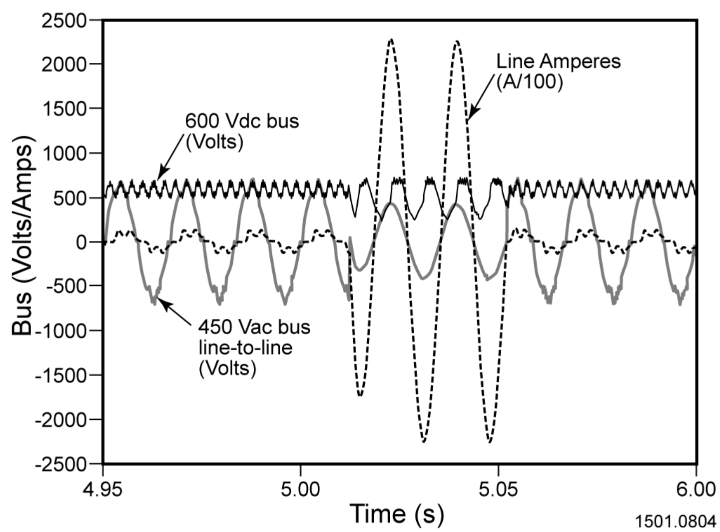

Figure 5. Transients upon low impedance fault line-to-line on the 450 Vac bus.

CONCLUSIONS

The joint modeling effort by the Center for Electromechanics of the University of Texas and the Naval Postgraduate School of an electric ship power system supporting multiple directed energy loads has been described. The models developed allow mimicking the ship's function in real time and furnish detailed information on the status and evolution of all significant physical parameters. This work focuses on capturing synergies and conflicts among power systems and pulsed loads before either is constrained, when the cost of system changes and optimization is the lowest.

REFERENCES

[1] W.B. Colson, J. Blau, K. Cohn, J. Jimenez, R. Pifer, "Free Electron Lasers in 2009," Proc. Free Electron Laser Conference (FEL2009), Liverpool, UK, p. 591, Aug. 23-28, 2009.

[2] http://www.onr.navy.mil/Media-Center/Fact-Sheets/Free-Electron-Laser.aspx.

[3] D. Douglas, "Optimization of Wall Plug Efficiency in a High-Power FEL System," Twelfth Annual Directed Energy Symposium, San Antonio, Nov. 4, 2009.